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Prediction of Slip for a Two-Wheel drive Tractor through MATLAB Simulink Model

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Abstract
The ability to pull is one of the primary distinctions between an automobile and a tractor. The tractor slippage has a significant impact on the pull. It is critical to keep slippage in the 8 to 15% range to achieve improved tractive efficiency, i.e., using more pull with the available power. As a result, slippage has a higher impact on the performance of a tractor-implement combination. Currently, slip is measured in the field using manual intervention. To solve this issue, a MATLAB Simulink model was developed to forecast the slip for a two-wheel drive tractor, and a micro-controller-based wheel slip measurement device was utilized to measure and validate the slip. In addition to saving time and costs, predicting slippage would lessen the laborious work that humans do during field testing. The developed model could also predict the actual speed of operation and the field capacity. The developed model predicted the slip within +4.03 to -4.55%, actual speed of operation within +3.83 to -2.70 % and field capacity within +3.44 to -7.09% relative deviation. The coefficient of determination was found close to 0.98 for all the three performance factors. The developed model is user friendly and efficient. This could help researcher to forecast the performance parameters without going to field.

Keywords: *MATLAB Simulink model, Tractor, Implement, Slip, Wheel slip measurement.*

1. Introduction
Amidst the increase in oil prices and labor expenses, considerable attention has been devoted to enhancing the productivity of tractor-implement combinations during field operations. Slip, as highlighted by Wismer and Luth (1972) and Brixius (1987), plays a significant role in optimizing tractive performance. [1, 2]. As tractive efficiency is optimal within this range, maintaining wheel slip within a specified optimal range ensures the tractor operates at maximum efficiency. [3]. There is no instrumentation in the current tractor system to display or measure this slip. In field testing, it is done manually. Despite the fact that, technology has been developed to measure the same. Wherein, two speed sensors are fitted onto front and rear wheel of the two-wheel drive tractor [4, 5, and 6]. In this study similar methodology was used to measure slip. Since slip is a major design factor for tractor-implement performance and current tractors doesn't have the set up to measure slip on the go hence field-testing methodology is the only way to identify slip. This methodology is labour intensive wherein, the marking of the field is required and manually counting the number of revolutions takes time. It is iterative process and different implements are tested to arrive at the result. Hence to overcome this problem, a MATLAB Simulink model-based design was developed that could predict the slip of the tractor while in operation with good accuracy. Since actual speed of operation and actual field capacity are also important parameters and it can be predicted if slip is predicted accurately. Therefore, these two

parameters were also predicted and included in this study. In order to save time and cost and also lessen laborious work, this study intent to predict slip, actual speed of operation and field capacity which are an important factor for performance of the tractor while on operation and it was validated by measuring slip via instrumentation.

2. Theoretical Considerations

To create a MATLAB Simulink Model-based design for forecasting slip, actual speed of operation, and field capacity, and the following theoretical and empirical equations were used.

2.1 Traction Prediction Models

Tractive performance of agricultural tractors was developed using the traction prediction equations of Brixius (1987). The following traction equations are taken into consideration in this study.

$$\mu_g = A_1(1 - e^{-A_2 B_n}) \times (1 - e^{-A_3 S}) + A_4 \quad (1)$$

$$B_n = \left(\frac{CI\ bd}{R_r}\right) \times \left(\frac{1 + A_5\frac{\delta}{h}}{1 + A_6\frac{b}{d}}\right) \quad (2)$$

$$MRR_r = \frac{A_7}{B_n} + A_4 + \frac{0.5 \times S}{\sqrt{B_n}} \quad (3)$$

Where, μ_g is gross thrust force coefficient, B_n is Brixius number, S is slip (%), b is wheel width (in.), d is wheel diameter (m), δ is tyre deflection, h is tyre section height (m), R_r is rear wheel dynamic weight, MRR_r is Motion resistance ratio and $A_1, A_2, A_3 \ldots A_7$ are coefficient's of traction. The coefficients are shown in Table 1 [1, 2].

Table 1 Recommended Traction Equation Coefficients

Traction Coefficient	A_1	A_2	A_3	A_4	A_5	A_6	A_7
Type of tire							
Bias ply	0.88	0.1	7.5	0.04	5	3	1
Radial ply	0.88	0.1	8.50-10.50	0.03-0.035	3	3	0.9

2.2 Reaction Forces in Tractor

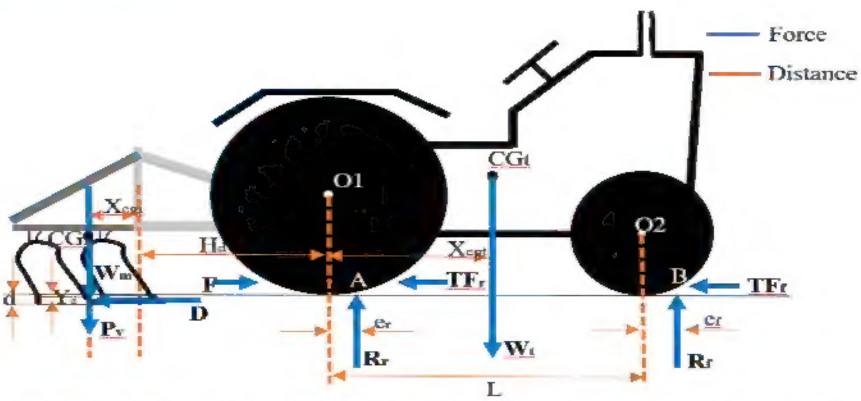

Figure 1 Forces Acting On Tractor-Implement Combination

Considering forces and moments in Figure 1, the dynamic wheel reactions were derived as in equation 4 and 5.

$$R_r = \frac{W_t(L + e_f - X_{cg}) + (W_m + P_y)(X_{cgi} + H_d + L + e_f) - DY_d}{L - e_r + e_f} \quad (4)$$

$$R_f = (W_t + W_m + P_y) - R_r \quad (5)$$

Where, CG_i is centre of gravity of implement, CG_t is centre of gravity of tractor, D is draft (kgf), d is depth of operation (m), e_r is eccentricity for front tire (m), e_f is eccentricity for rear tire (m), F is gross thrust force (kgf), H_d is distance between rear axle center and link point of the tractor(m), L is wheel base of the tractor (m), P_y is vertical force (kgf), R_f is front wheel reaction (kgf), R_r is rear wheel reaction (kgf), TF_f is towed force front (kgf), TF_r is towed force rear (kgf), W_m is weight of implement (kg), W_t is weight of the tractor (kg), X_{cgi} is distance between link point and center of gravity of implement (m), X_{cgt} is distance

between rear axle center and center of gravity of tractor (m) and Y_d is center of resistance distance to ground surface (m) [4,5,6].

2.3 ASABE Draft Prediction Model

In the software calculation, the existing ASABE draft model was employed to forecast the draft. Equation 6 expresses it [7].

$$D = F_j(A + BV_a + CV_a^2) \times W \times d \qquad (6)$$

In the given equation, D represents the draft in kilograms, while F_j denotes the dimensionless soil texture adjustment, with j taking values of 1 for fine soil, 2 for medium soil, and 3 for coarse soil. Parameters A, B, and C are specific to the machine [8] , W represents the width in meters or the number of tines, d stands for the depth of operation in centimeters, and V_a indicates the actual velocity in kilometers per hour. The machine and soil specific parameters as suggested in ASABE draft model are given in Table 2.

Table 2 Machine Specific Parameters

Implement	Tillage	Number of tines	Machine parameter			Soil Specific parameters		
			A	B	C	F_1	F_2	F_3
Cultivator	Primary	7,9, 11… etc.	42	2.8	0	1	0.85	0.65
	Secondary		32	1.9	0	1	0.85	0.65

2.4 Traction Performance Indices

2.4.1 Motion Resistance Ratio (MRR)

Motion resistance, also referred to as the motion resistance ratio (MRR), and represents the relationship between rolling resistance and the dynamic weight applied to the wheel [9].

2.4.2 Gross Traction Ratio (GTR)

The gross traction ratio denotes the proportion of the tractor's gross thrust to the dynamic weight exerted on the traction wheels (powered wheels).

2.4.3 Net Traction Ratio (NTR)

The net traction ratio is the ratio of draft to the dynamic weight on the driving wheels. It can be computed using two methods, as outlined in equations 7 and 8.

$$NTR_a = \frac{D}{R_r} \qquad (7)$$

$$NTR_b = GTR - MRR \qquad (8)$$

2.4.4 Wheel Slip (%)

When a tractor pulls a load, the distance traveled and/or speed decrease due to flexing of the tractive device and shear within the soil [10]. Slip occurs when a wheel or traction device experiences pull (net traction). It is given by equation 9.

$$S = (1 - \frac{V_a}{V_t}) \times 100 \qquad (9)$$

Where s is slip (%), $V_a$is actual velocity (km/hr) and V_t is theoretical velocity (km/hr).

2.4.5 Field Capacity (Ha/hr)

It is defined as the actual area covered within a given time.

3. Software Development in MATLAB Simulink

Using MATLAB Simulink 2020a, a program was created to forecast slip, real operating speed, and field capacity. Figure 2 depicts the development process for the same Vis flow chart. The program was first fed with the input parameters. Input parameters were tractor static weight (Kg), weight of Implement (Kg), Hd (m), Xcgt(m), Xcgi(m), depth of operation(m), theoretical velocity, width of implement(m) and type of tire. The software first used equation 6 to determine the implement's draft based on the state of the soil. Next, every traction parameter was computed using equations 1, 2, 3, 7, 8, and 9. Motion resistance ratio (MRR) and slip were initially considered to be 0.04 and 0.02 respectively. They were then increased iteratively depending on if-else conditions. Based on the difference between MRR andMRR_r, the MRR was increased and supplied as feedback to the program. Similarly, for slip difference between NTR_a - NTR_b was considered. After arriving at slip, the actual speed of operation and the field capacity can easily be calculated.

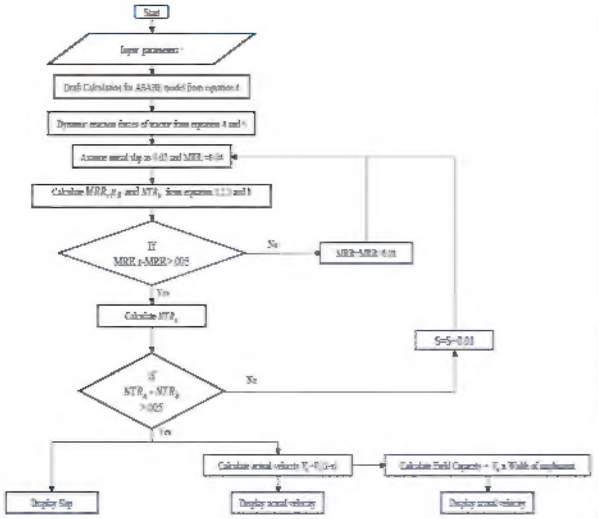

Figure 2 **Flow Chart for Developed Software**

4. Instrumentation for Software Validation

The tractor was equipped with standard tires sized 6-16 and 13.6-28 on the front and rear axles, respectively. Slip was determined using two measurements: the actual and theoretical speeds of the tractor. The theoretical speed was calculated based on the average rotational speed (rpm) of the rear wheels, while the actual speed was obtained from The front wheel. The front wheel had reluctor rings with 44 slots, while the rear wheel speed was measured by assessing the gear speed between the range gear and final drive. The rear reluctor ring was affixed to the rear axle shaft and secured to the flange using serrated wheel bolts, with the rear sensor bracket mounted at the rear axle center. Conversely, the front reluctor ring was mounted on the front wheel hub, and the sensor bracket was bolted onto the knuckle arm. Both configurations are depicted in Figure 3. Angular speed signals from the transmission gear and front wheel were generated through the transmission gear and reluctor ring at the front wheel, respectively. These signals, along with wheel speed sensors, were transmitted to a microcontroller for slip calculation. The signals received from the rear sensors were utilized to determine the theoretical speed by multiplying the average readings with the distance traveled by the rear wheel in one revolution on a hard surface. Similarly, the average output of the front wheel sensor was multiplied by the distance travelled by the front wheel in one revolution to determine the actual forward speed. The wheel speed data were input to a microcontroller for slip calculation and digital display presentation. [11-15].

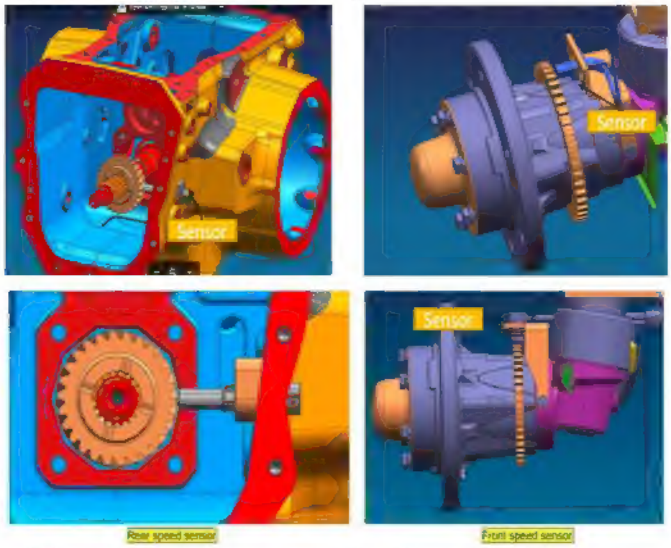

Figure 3 **Arrangement for Speed Sensor and Reluctor Ring**

1. Results and Discussion

The developed model as shown in Figure 4 using the control algorithm as shown in Figure 2 had to be validated. To validate the same a 45 hp Mahindra 575 DI tractor along with M&M Limited /360023 9 tine cultivator was used. The result of the experiment is shown in Table 3. Wherein, the operated gear was H1 and M3 as recommended by manufacturer and the throttle was varied from 1600 to 1700. The cone index was 500±50 Kpa measured using cone penetrometer. The developed model predicted the slip within +4.03 to -4.55% relative variation [16]. ((Predicted- experimental) x (100/Experimental)), actual speed of operation within +3.83 to -2.70 % relative variation and field capacity within +3.44 to -7.09% relative variation [17]. To predict the accuracy of the model, the predicted slip vs experimental slip, the predicted actual speed vs experimental actual speed, the predicted field capacity vs experimental filed capacity were plotted as shown in Figure 5 ((a),(b) and (c)). Results indicated a good correlation with coefficient of determination of (R^2) 0.9727for slip, 0.9763 for actual speed and 0.9763 for field capacity.

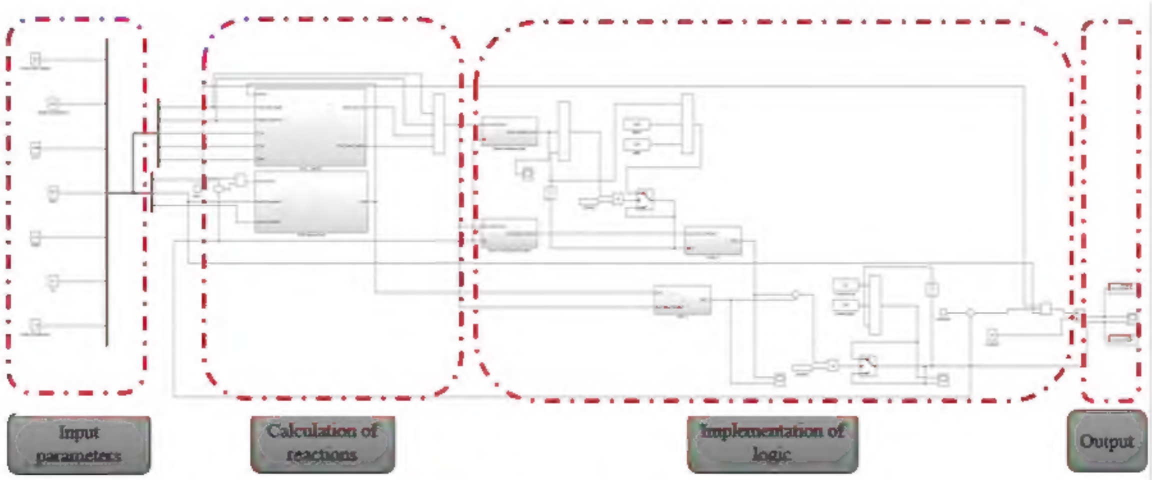

Figure 4 Developed Model

Table 3 Experimental Versus Predicted Data

Gear	Throttle (rpm)	Slip (%)			Actual Speed (Km/hr)			Field Capacity (Ha/hr)		
		Experimental (E)	Predicted (P)	Variation (%) (P-E)*100/E	Experimental (E)	Predicted (P)	Variation (%) (P-E)*100/E	Experimental (E)	Predicted (P)	Variation (%) (P-E)*100/E
H1	1600	16.60	17.00	2.41	5.59	5.53	-1.07	1.41	1.31	-7.09
H1	1700	14.90	15.50	4.03	6.03	5.96	-1.16	1.23	1.22	-0.81
H1	1800	17.00	17.10	0.59	6.23	6.08	-2.36	1.27	1.24	-2.36
H1	1900	18.00	17.50	-2.78	6.5	6.66	2.48	1.33	1.36	2.26
H1	2000	19.00	18.50	-2.63	6.76	6.76	-0.07	1.38	1.39	0.72
H1	2100	19.10	19.00	-0.52	7.09	7.36	3.84	1.45	1.50	3.45
H1	2200	19.20	19.00	-1.04	7.41	7.62	2.82	1.36	1.35	-0.74
M3	1600	20.10	20.00	-0.50	6.66	6.62	-0.60	1.43	1.41	-1.40
M3	1700	21.00	20.50	-2.38	7.00	6.90	-1.43	1.52	1.47	-3.29
M3	1800	21.00	20.50	-2.38	7.41	7.21	-2.70	1.58	1.56	-1.27
M3	1900	22.00	21.00	-4.55	7.72	7.62	-1.31	1.64	1.62	-1.22
M3	2000	23.00	22.00	-4.35	8.03	8.00	-0.37	1.75	1.72	-1.71
M3	2100	22.00	21.00	-4.55	8.54	8.40	-1.64	1.78	1.76	-1.12
M3	2200	24.00	23.20	-3.33	8.72	8.60	-1.38	1.79	1.78	-0.56

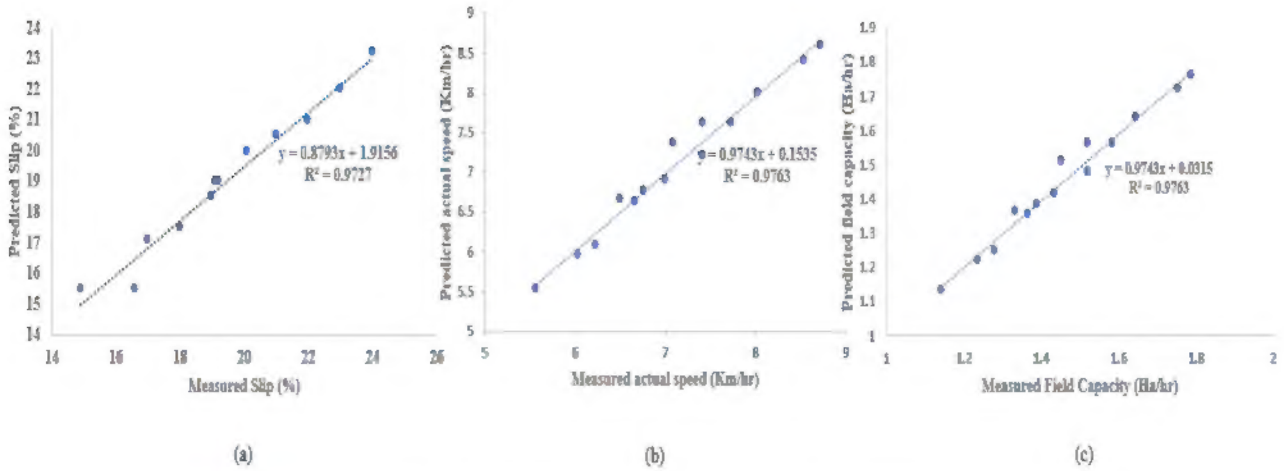

Figure 5 Predicted vs Experimental Graph for Output Parameters

Conclusion

A model-based user-friendly software was developed for predicting slip, actual speed of operation and field capacity since they are predominant parameters to evaluate tractor-implement combination performance [18]. This study also includes the methodology to measure slip and validate the same by instrumentation which may be quite useful for researchers and engineers. The developed software was validated with experimental actual field results and found very close prediction for different operating parameters.

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